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UNITED STATES PATENT APPLICATION FOR

MULTI FREQUENCY MAGNETIC DIPOLE ANTENNA STRUCTURES FOR VERY LOW-PROFILE ANTENNA APPLICATIONS

Inventors: Gregory Poilasne
Laurent Desclos
Sebastian Rowson

Prepared by:

BLAKELY, SOKOLOFF, TAYLOR & ZAFMAN LLP
12400 Wilshire Boulevard
Seventh Floor
Los Angeles, California 90025
(310) 207-3800

BACKGROUND OF THE INVENTION

1. REFERENCES TO RELATED APPLICATIONS

[0001] This application is related to our co-pending application Serial No. 09/892,928 filed on June 26, 2001, entitled "Multi Frequency Magnetic Dipole Antenna Structure and Methods of Reusing the Volume of an Antenna", and incorporated herein by reference.

[0002] This application also relates to U.S. Patent No. 6,323,810, entitled "Multimode Grounded Finger Patch Antenna" by Gregory Poilasne et al., which is owned by the assignee of this application and incorporated herein by reference.

[0003] Furthermore, this application relates to co-pending application Serial No. 09/781,779, entitled "Spiral Sheet Antenna Structure and Method" by Eli Yablonovitch et al., owned by the assignee of this application and incorporated herein by reference.

2. FIELD OF THE INVENTION

[0004] The present invention relates generally to the field of wireless communications, and particularly to the design of an antenna.

3. BACKGROUND

[0005] Small antennas are required for portable wireless communications. With classical antenna structures, a certain physical volume is required to produce a resonant antenna structure at a particular radio frequency and with a particular bandwidth. A fairly large volume is required if a large bandwidth is desired. Our previously filed application no. 09/892,928 addresses the need for a small compact antenna with wide bandwidth. The present invention addresses the need for a wide-bandwidth, compact antenna that has a very low profile.

SUMMARY OF THE INVENTION

[0006] The present invention provides a capacitively loaded magnetic dipole with an E-field distribution so that the thickness of the antenna can be reduced while still maintaining high efficiency. The basic antenna element comprises a ground plane; a first conductor extending longitudinally above the ground plane having a first end electrically connected to the ground plane; a second conductor extending longitudinally above the ground plane and parallel to the first conductor, the second conductor also having a first end electrically connected to the ground plane; and an antenna feed coupled to the first conductor. Both of the conductors are spaced equidistantly above the ground plane. Additional parasitic elements, which may be parallel or non-parallel to the driven element, may be used to increase the bandwidth of the antenna. The parasitic elements are tuned to a slightly different frequency in order to obtain a multi-resonant antenna structure. The frequencies of the resonant modes can either be placed close enough to achieve the desired overall bandwidth or can be placed at different frequencies to achieve multi-band performance. Various embodiments are disclosed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] **Figure 1** conceptually illustrates the antenna designs of the present invention.

[0008] **Figure 2** illustrates the increased overall bandwidth achieved with a multiresonant antenna design.

[0009] **Figure 3** is an equivalent circuit for a radiating structure.

[0010] **Figure 4** is an equivalent circuit for a multiresonant antenna structure.

[0011] **Figure 5** illustrates a basic radiating element of a low profile embodiment of the present invention.

[0012] **Figure 6** illustrates the field configuration for the basic element shown in **Figure 5**.

[0013] **Figure 7** illustrates a low-profile antenna having a driven element and additional parasitic elements.

[0014] **Figure 8** is a Smith chart illustrating a non-optimized multiresonant antenna.

[0015] **Figure 9** is a Smith chart illustrating an optimized multiresonant antenna.

[0016] **Figure 10** illustrates an antenna according to the present invention with non-parallel radiating elements.

[0017] **Figure 11** is a perspective view of an antenna of the present invention comprising multiple elements, some tuned to a frequency f1 and some others tuned to a frequency f2.

[0018] **Figure 12** shows how the antenna of the present invention can be implemented within an electronic device, with electronic components around it, without disturbing the antenna behavior.

[0019] **Figure 13** illustrates an antenna of the present invention used in a polarization diversity context.

[0020] **Figures 14a-14d** illustrate antennas of the present invention designed to exhibit a plurality of frequency and/or polarization modes.

[0021] **Figure 15** illustrates an antenna of the present invention with radiating elements of different heights and placed at different levels.

[0022] **Figure 16** illustrates an antenna of the present invention where the driven element is fed by a coaxial waveguide.

[0023] **Figure 17** illustrates an antenna of the present invention where the driven element is fed by a coplanar waveguide or a micro-strip line.

[0024] **Figure 18** illustrates an antenna of the present invention in a configuration where the radiated field has a circular polarization.

[0025] **Figure 19** shows how a basic element of the antenna can be made of conductive material.

[0026] **Figure 20** shows how a basic element of the antenna can be made using a flexible substrate placed inside an enclosure.

[0027] **Figure 21** shows an antenna of the present invention that is modified for increased bandwidth.

[0028] **Figure 22** illustrates an alternative antenna structure with increased bandwidth.

[0029] **Figure 23** illustrates the magnetic field of the antenna structure of **Figure 22**.

[0030] **Figure 24** illustrates a highly resonating antenna element of the present invention in combination with a wide-bandwidth element.

DETAILED DESCRIPTION OF THE INVENTION

[0031] In the following description, for purposes of explanation and not limitation, specific details are set forth in order to provide a thorough understanding of the present invention. However, it will be apparent to one skilled in the art that the present invention may be practiced in other embodiments that depart from these specific details. In other instances, detailed descriptions of well-known methods and devices are omitted so as to not obscure the description of the present invention with unnecessary detail.

[0032] The volume to bandwidth ratio is one of the most important constraints in modern antenna design. One approach to increasing this ratio is to re-use the volume for different orthogonal modes. Some designs, such as the Grounded Multifinger Patch disclosed in patent application Serial No. 09/901,134, already use this approach, even though the designs do not optimize the volume to bandwidth ratio. In the previously mentioned patent application, two modes are generated using the same physical structure, although the modes do not use exactly the same volume. The current repartition of the two modes is different, but both modes nevertheless use a common portion of the available volume. This concept of utilizing the physical volume of the antenna for a plurality of antenna modes is illustrated generally in **Figure 1**. V is the physical volume of the antenna, which has two radiating modes. The physical volume associated with the first mode is designated V1, whereas that associated with the second mode is designated V2. It can be seen that a portion of the physical volume, designated V12, is common to both of the modes.

[0033] We will express the concept of volume reuse and its frequency dependence with what we refer to as a "K law". The common general K law is defined by the following:

$$\Delta f/f = K \bullet V/\lambda^3$$

[0034] $\Delta f/f$ is the normalized frequency bandwidth. λ is the wavelength. The term V represents the volume that will enclose the antenna. This volume so far has been a metric and no discussion has been made on the real definition of this volume and the relation to the K factor.

[0035] In order to have a better understanding of the K law, different K factors are defined:

K_{modal} is defined by the mode volume V_i and the corresponding mode bandwidth:

$$\Delta f_i/f_i = K_{modal} \bullet V_i/\lambda_i^3$$

where i is the mode index.

K_{modal} is thus a constant related to the volume occupied by one electromagnetic mode.

$K_{effective}$ is defined by the union of the mode volumes $V_1 \cup V_2 \cup .. V_i$ and the cumulative bandwidth. It can be thought of as a cumulative K;

$$\sum_i \Delta f_i / f_i = K_{effective} \bullet (V_1 \cup V_2 \cup .. V_i) / \lambda_C^3$$

where λ_c is the wavelength of the central frequency.

$K_{effective}$ is a constant related to the minimum volume occupied by the different excited modes taking into account the fact that the modes share a part of the volume. The different frequencies f_i must be very close in order to have nearly overlapping bandwidths.

$K_{physical}$ or $K_{observed}$ is defined by the structural volume V of the antenna and the overall antenna bandwidth:

$$\Delta f/f = K_{physical} \bullet V/\lambda^3$$

[0036] $K_{physical}$ or $K_{observed}$ is the most important K factor since it takes into account the real physical parameters and the usable bandwidth. $K_{physical}$ is also referred to as $K_{observed}$ since it is the only K factor that can be calculated experimentally. In order to have the modes confined within the physical volume of the antenna, $K_{physical}$ must be lower than $K_{effective}$. However these K factors are often nearly equal. The best and ideal case is obtained when $K_{physical}$ is approximately equal to $K_{effective}$ and is also approximately equal to the smallest K_{modal}. It should be noted that confining the modes inside the antenna is important in order to have a well-isolated antenna.

[0037] One of the conclusions from the above calculations is that it is important to have the modes share as much volume as possible in order to have the different modes enclosed in the smallest volume possible.

[0038] For a plurality of radiating modes i, **Figure 2** shows the observed return loss of a multiresonant structure. Different successive resonances occur at the frequencies $f_1, f_2, f_i, \ldots f_n$. These peaks correspond to the different electromagnetic modes excited inside the structure. **Figure 2** illustrates the relationship between the physical or observed K and the bandwidth over f_1 to f_n.

[0039] For a particular radiating mode with a resonant frequency at f_1, we can consider the equivalent simplified circuit L_1C_1 shown in **Figure 3**. By neglecting the resistance in the equivalent circuit, the bandwidth of the antenna is simply a function of the radiation resistance. The circuit of **Figure 3** can be repeated to produce an equivalent circuit for a plurality of resonant frequencies.

[0040] **Figure 4** illustrates a multiresonant antenna represented by a plurality of LC circuits. At the frequency f_1 only the circuit L_1C_1 is resonating. Physically, one part of the antenna structure resonates at each frequency within the covered spectrum. Again, neglecting real resistance of the structure, the bandwidth of each mode is a function of the radiation resistance.

[0041] As discussed above, in order to optimize the K factor, the antenna volume must be reused for the different resonant modes. One example of a multimode antenna utilizes a capacitively loaded microstrip type of antenna as the basic radiating structure. Modifications of this basic structure will be subsequently described. In all of the described examples, the elements of the multimode antenna structures have closely spaced resonant frequencies.

[0042] The concept of utilizing the physical volume of the antenna for a plurality of antenna modes has been described in our earlier application. In the embodiments described therein, different modes are excited using one excited element and additional parasitic elements tuned to a slightly different frequency. The magnetic coupling between the different elements is enough to excite the different resonances. With reference to **Figure 5**, different embodiments will now be described in which the two conductors of a radiating element are at the same z elevation in an x-y plane rather than being in an x-z plane as was the case in our earlier application. For the antenna structure of **Figure 5**, the two conductors are spaced apart by a distance Δy. The electric field is horizontal as shown in **Figure 6**. The horizontal E-field reduces the interaction with the ground plane, and the height of the antenna can be reduced while keeping the same electromagnetic characteristics. Even if the electric field interacts with the ground, its configuration remains nearly identical.

[0043] Multiple elements can be placed parallel to each other as shown in **Figure 7**. Here, only one element is driven and the others are parasitic. There is a magnetic coupling between the main, driven element and the parasitic elements. This magnetic coupling creates multiple resonances. If the resonances are close enough in frequency, then it is possible to have a wide bandwidth antenna, keeping a small volume and a low profile. Impedence matching of this structure is illustrated by the Smith chart shown in **Figure 8**. The large outer loop 50 corresponds to the main driven element 40, whereas the smaller loops 51-53 correspond to the parasitic

elements. This is a representation of a non-optimized structure. Various adjustments can be made to the antenna elements to influence the positions of the loops on the Smith chart. The smaller loops may be gathered in the same area in order to obtain a constant impedance within the overall frequency range.

[0044] In the case of a typical 50 ohm connection, an optimized structure will have all of the loops gathered approximately in the center of the Smith chart as shown in **Figure 9**. In order to gather the loops in the center of the Smith chart (or wherever it is desired to place them), the dimensions of the individual antenna elements are adjusted, keeping in mind that each loop corresponds to one element.

[0045] With reference to **Figure 10**, the different elements do not have to be parallel to obtain the desired behavior. This actually gives greater flexibility in matching the antenna to the impedance of the feeding point, which may be 50 ohms or may be a different value as a matter of design choice.

[0046] **Figure 11** is a perspective view of an antenna structure composed of one driven element and multiple parasitic elements tuned to frequencies nearby the frequency f1 of the driven element and also to frequencies around another frequency f2 completely different from the driven element frequency. Multiple excited elements can also be considered in order to relax the constraints.

[0047] One very interesting feature of the antenna structure presented here is that electronic and structural components can be inserted in between the different radiating elements as shown in **Figure 12** without disturbing the behavior of the overall antenna.

[0048] The use of orthogonal modes is important for achieving volume re-use. To be orthogonal, the modes must either be at slightly different frequencies or they must have orthogonal polarization. Two orthogonal polarized modes at the same frequency can be obtained by placing two radiating elements orthogonal to one another. For example, **Figure 13** shows a structure where two antennas composed of three elements each are placed orthogonally in order to obtain some polarization diversity in the same volume. Each antenna has its own feeding point and they both work within the same frequency band.

[0049] Other different configurations can be considered depending on the electromagnetic characteristics targeted and the space available in the enclosure where the antenna has to be mounted. **Figures 14a-14d** present four other possibilities where multiple elements are placed using a plurality of modes (frequency and polarization). Where elements intersect, as in **Figures**

14b and 14d, the elements may or may not be in electrical contact at the different levels. As shown in **Figure 15**, the different radiating elements do not have to have the same height and do not need to be on the same level.

[0050] Different types of feed arrangements can be considered for this new capacitively loaded magnetic dipole. One of the most classic feeding solutions is to use a coaxial cable. As shown in **Figure 16**, the inner part of the coaxial cable is soldered to one point of the antenna and the outer part is soldered to another point, so that an inductance can be created in between to match the input to whatever impedance is needed. It is also possible to use a coplanar waveguide or micro-strip line as a feeding system as shown in **Figure 17**. In such case, one point of the antenna is soldered to the central line, and another part of the antenna is soldered to the ground of the guide. When used with multiple elements working within one frequency band, only one element is connected to the line; the other elements are just passive. In the case of a multi-band antenna, different elements can be driven so that it is possible to match the antenna in the different frequency bands with only one feeding point. Multiple feeding points can also be used.

[0051] It is possible to obtain a circularly polarized antenna by placing two elements perpendicular to one another as shown in **Figure 18**. The two elements must be placed in a non-symmetrical relationship so that the magnetic coupling between them does not cancel.

[0052] The basic radiating element of a low profile capacitively loaded magnetic dipole antenna according to the present invention can be made in various ways. One approach utilizes a strip of a conductive material such as copper, which is simply folded in order to obtain the shape shown in **Figure 19**. Tolerances can be maintained by using suitable stand-offs made of an insulating material such as a composite, for example.

[0053] A more complete solution is presented in **Figure 20**. In this case, the two conductors of the radiating element are printed on a piece of flexible material with one pad at one extremity of each conductor. This piece of flexible material can then be mounted directly to the surface of the enclosure for the device, such as a cellular telephone, to which the antenna is connected. A circuit board within the enclosure may include the ground plane. Spring contacts may be mounted to the circuit board to make the electrical connection between the ground plane and the two conductors of the radiating element. The feeding system is simply printed on the circuit board and is placed right under the element.

[0054] The radiating elements previously described are highly resonant and therefore exhibit a narrow bandwidth. In some applications, it is desirable to increase the bandwidth of the radiating element. One solution is to relax the field confinement inside the capacitance. One way

of accomplishing this is to increase the gap between the conductors as shown in **Figure 21**. While this is effective in reducing the capacitance and thereby increasing the bandwidth of the element, it also greatly increases the dimensions of the antenna.

[0055] Another solution is illustrated in **Figure 22**. The radiating element comprises a generally "U"- shaped conductor connected to the ground plane at the base of the "U". One leg of the "U"- shaped conductor is short-circuited to the ground plane adjacent to the feed point. As a result, part of the current propagating along the top surface of the "U"- shaped conductor sees a capacitance where the electromagnetic field is confined and the rest of the current propagates along the conductor behaving like an inductance. As in the case of the highly resonant antenna element, the radiating characteristics of the "U"- shaped element are associated with the magnetic field expelled from the side of the antenna as shown in **Figure 23**. Less electric field is confined inside the antenna and the bandwidth is greatly improved while still maintaining reasonably good isolation.

[0056] The distance between the two legs of the "U"- shaped conductor is very important since it defines the size of the current loop that expels the magnetic field. As with the previously described embodiments, one or more parasitic elements can be magnetically coupled to a driven element as shown in **Figure 24**. The parasitic element, which is shown here to be a highly resonant element, may be placed either to the side of the driven element or underneath it.

[0057] It will be recognized that the above-described invention may be embodied in other specific forms without departing from the spirit or essential characteristics of the disclosure. Thus, it is understood that the invention is not to be limited by the foregoing illustrative details, but rather is to be defined by the appended claims.